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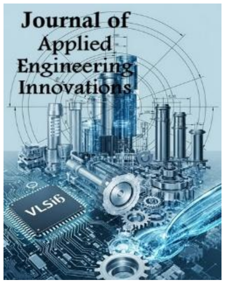

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Research Article

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Organic Ranking Cycle–Stirling Engine Efficiency in Small Scale Industrial Solar Energy Conversion in Delta State, Nigeria

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Abstract: This study analyzed the performance of hybrid ORC -Stirling systems in terms of thermal-mechanical energy conversion in relation to small-scale power generation by industries in Delta state, Nigeria. The two main parameters examined included the thermal collection efficiency of evacuated tube collectors and the influence of the environmental parameters on the stability of torque and the power output of the shaft. The data collection was performed on solar irradiance, ambient temperature, wind speed and PCM thermal cycling at 8-hour intervals in 90 days, and analyzed by means of MATLAB-simulated multidimensional plots. Findings showed that evacuated tube collection produced efficiency of ≥65% thermal collection efficiency, providing sufficient heat input for ORC–Stirling systems to maintain torque deviations within ±5% and conversion efficiency ≥40%. Mean solar irradiance of 775 W/m² and PCM cycling between 250–310 °C supported continuous 8-hour daily operation of industrial machinery. The results showed that hybrid ORC-Stirling systems are reliable to drive small-scale industrial processes even when environmental conditions vary. It was therefore advised that the small-scale operators should invest in ORC-Stirling systems, the Manufacturer Association of Nigeria (Delta State Chapter) should create awareness and demonstrations of this hybrid ORC-Stirling system and tertiary institutions in Delta state should engage the faculties of Mechanical Engineering to conduct training and pilot projects to facilitate adoption and proper maintenance of this ORC-Stirling system. Such measures will further improve operational stability, cut down-time and sustainability and decentralized industrial power.

Keywords: ORC–Stirling system, Evacuated tube collector, Thermal-to-mechanical conversion, Small-scale industry.

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Conflict of interest: None

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Introduction

Thermalized energy conversion systems which combine solar collectors with mechanical prime movers rely on controlled heat capture, controlled heat transfer pathways and stable thermodynamic cycling for provision of usable mechanical output. Evacuated tube collectors offer mechanically efficient source of heat due to the vacuum insulation, the cylindrical design of the absorber and the use of coatings on the surface, which together reduce the convective losses and maintain high fluid temperatures under varying levels of irradiance [1]. When coupled to an Organic Rankine Cycle (ORC)-Stirling engine configuration, these collectors provide thermal input which is suitable for continuous cyclic expansion and compression processes. The ORC component, which is characterised by the use of organic working fluids, i.e. hydrocarbon-based refrigerants and light alkanes, which allows to effectively utilise the heat at relatively low temperatures and pressures, thus conditioning the thermal energy before its mechanical conversion [2]. In addition to standalone ORC or Stirling systems, which can both independently generate mechanical power, the combined ORC-Stirling architecture takes advantage of thermodynamic complementarity, in the form of regulated heat delivery to stabilise the piston movement and minimise irreversibilities in the cyclic operation [3]. This hybridisation helps to better match the temperatures between the heat exchangers, and a better pressure-volume coherence within the Stirling engine that leads to more constant shaft power output for variable heat flux [4,5]. Consequently, the performance envelope of the integrated system is determined by the performance characteristics of its individual components: collector thermal efficiency, the behaviour of the working fluid and the effectiveness of the mechanical coupling [6].

Mechanical systems combined with ORC and Stirling technologies provide an attractive solution for displacing traditional fossil-fuelled engines for use in many lows to mid-grade industrial applications. Their inherent modularity, thermal efficiency and ability to hybridise with thermal storage systems, such as those that use phase change materials (PCMs), make them suitable for decentralised mechanical power generation in rural and semi-urban industrial clusters [7,8]. This configuration allows for distributed energy solutions which can provide continuous rotational power to industrial machinery without having to be connected to the grid or have a diesel-based backup. Equipment like Rice mills, which usually use mechanical shaft power to perform operations like drying, dehusking and polishing, can greatly benefit from the adaptability and efficiency of ORC-Stirling systems [9]. These machines need to provide certain levels of torque for long durations and within these levels, temperature control and mechanical stability are key. However, small-scale industrial implementations of such systems are hampered by challenges in the form of heat losses as well as by environmental factors which impact the efficiency of the thermal-to-mechanical conversion. Losses via piping, engine housing and heat exchanger surfaces reduce the available temperature differential and so reduce torque generation and reducing long term system reliability [10]. In environments such as Delta State, Nigeria where the performance of solar irradiance and the ambient temperature changes, the combined effect of these parameters is important in optimising system performance [11,12]. Without considering such environmental and operational factors, the efficiency predictions of hybrid ORC-Stirling systems may be too optimistic [13]. A thorough assessment of the heat losses and the environmental impacts is thus critical to the practicality of ORC-Stirling systems as a valid energy source for small-scale industrial purposes.

Statement of the Problem

Small-scale industrial enterprises in Delta State, Nigeria need mechanical power to maintain their operations like drying, milling, polishing and processing materials, which need to have a stable and constant feature. However, such industries are presently limited by high dependency on conventional and non-renewable energy sources for which the acquisition, maintenance and fuel costs are continuously increasing unpredictably, whilst contributing to environmental degradation and occupational health risks at the same time. The growing need for improved mechanical reliability and cost effective energy options such as hybrid ORC-Stirling, has become a more important interest in finding cleaner thermal to mechanical energy conversion systems. Yet there is still uncertainty in the practical use of hybrid ORC-Stirling configurations for small-scale industrial solar energy conversion in Delta State, Nigeria due to pending challenges related to thermal performance of the collectors, thermal losses and sensitivity to environmental variations, necessitating a focused investigation.

Aim and Objectives of the Study

This study was aimed at investigating ORC-Stirling engine efficiency in small scale industrial solar energy conversion in Delta State, Nigeria. Specifically, the objectives were to:

1. Study the thermal efficiency of evacuated tube collectors and their influence on ORC–Stirling engine performance for small-scale industrial solar energy conversion under varying solar irradiance in Delta State, Nigeria.
2. Ascertain how heat losses and environmental effects impact the thermal-to-mechanical conversion efficiency of ORC–Stirling engine in small-scale industrial solar energy conversion systems in Delta State, Nigeria.

Research Questions

1. What is the thermal efficiency of evacuated tube collectors, and how does it influence ORC–Stirling engine performance in small-scale industrial solar energy conversion under varying solar irradiance in Delta State, Nigeria?
2. What is the impact of heat losses and environmental effects on the thermal-to-mechanical conversion efficiency of ORC–Stirling engine in small-scale industrial solar energy conversion systems in Delta State, Nigeria?

Literature Review

Mechanical power systems that depend on solar-thermal conversion of low to medium grade heat to useful shaft work by controlled thermodynamic cycling has been studied in detail. Such systems involve evacuated tube collectors because the vacuum insulation can be used to suppress the convective loss and enables the stagnation temperatures to be higher in the period of varying irradiance of the sun, stabilizing the thermal input to prime movers downstream [1,14]. The absorber coatings and selective surface treatment have also been further added to enhance the radiative absorption and lower the emissivity leading to quantifiable increases in the collector efficiency [15,16]. Together with Organic Rankine Cycles, these collectors enable the development of effective energy recovery of moderate temperature energy sources with organic working fluids having low boiling points and favourable expansion ratios [17]. Stirling engines are complementary to this procedure since they rely on closed regeneration cycles, which allow most of the expansion and compression to be nearly isotopic and achieves a better theoretical conversion efficiency in constant thermal gradients [18].

Combination of ORC and Stirling subsystems have been demonstrated to contribute to the enhancement of the thermodynamic matching, cyclic irreversibilities and the stabilization of the shaft output during the varying heat input [3]. Studies of heat exchanger optimisation also discover that enhanced convective heat transfer coefficients and controlled thermal pathways make a substantial influence on the system operation and experimental tests of solar driven thermal loads have demonstrated that temporary heat flux changes can have a strong effect on the expansion behaviour and power stability. Hybrid ORC-Stirling architectures have been suggested which attempt to more closely match the thermal interface between subsystems, reduce entropy generation, stabilize mechanical output at variable heat supply [3]. The design of heat exchangers is also decisive due to the fact that the impact of increase of convective transfer coefficients and optimization of flow geometry to make use of existing thermal energy increase are enhanced [4].

Experimental studies also show that temporary heat loading has a direct effect on the dynamics of expansion, pressure-volumetric and consistency of the output in solar driven systems [5]. Although all these advancements have been made in theory and experimental models, the actual application of the ORC-Stirling systems is severely constrained by inherent losses of heat and other environmental changes. The interfaces with the thermal dissipation to the piping and insulation, engine casings and open surfaces on exchangers inhibit the available temperature difference and consequently directly reduce the mechanical output [10].

Radiative and convective losses are also intensified under diverse changing ambient conditions that, as observed in other works, do not only influence steady-state operation but also reduce the cyclic efficiency [19]. To mitigate these effects, thermal energy storage media have been considered as the buffering systems, yet the success of this solution relies on the predictability of the climatic conditions, not to mention the predictability of the load profiles [20]. The environment-environmental coupling is highly significant in the tropical regions with a high level of humidity like in southern Nigeria, where divergent irradiance and high ambient temperature are observed [12,11]. Through additional performance experiments of solar-thermal-powered energy harvesting systems, it is shown that local weather conditions play a major role on the nature of heat transfer, working-fluid behaviour and mechanical stability that cannot be elucidated in an idealized theoretical framework [6].

Theoretical Framework

The theory of thermal energy harvesting is based on the principle of classical thermodynamics according to which usable mechanical energy may be derived out of heat when a constant temperature gradient is present across an energy conversion system. This framework can be applied to the current research because it describes the working principles of evacuated tube collectors to control the amount of heat captured and transferred to hybrid ORC-Stirling engines to provide a lasting mechanical energy [1]. Its analytical impact is supported by the research that notes that the conversion efficiency is determined by the joint presence of latitudinal paths of heat transfer, the behavior of working fluids, and cyclic stability [17,4].

Materials and Method

This study adopted a simulation based approach to investigate the thermal to mechanical conversion efficiency and torque stability of hybrid ORC-Stirling type device under various solar irradiance and environmental conditions in Delta State, Nigeria. Materials used were evacuated tube solar collectors (ETCs), latent heat storage tank, Stirling and ORC engines, heat transfer fluids, thermal exchangers, torque and revolutions per minute (RPM) sensors, insulated storage tanks, mechanical load test benches (i.e. rice mills and cassava graters), control valves and flow meters and the software was the Matlab/Simulink to model the system. Local weather data such as solar irradiance, ambient temperature and wind speed were obtained during a 90 days duration in order to simulate actual operating conditions.

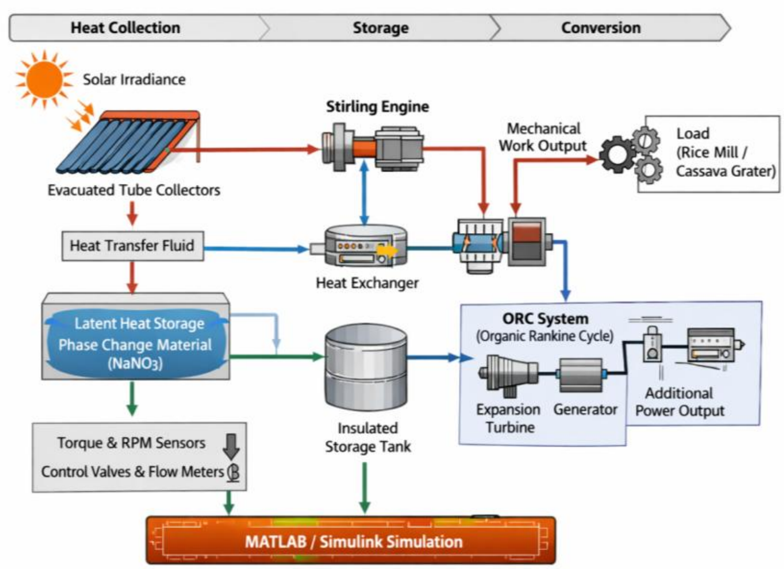

Figure 1: Study's materials and method model
Source: Self design

Thermal and mechanical subsystems have been combined into a schematic system model in Figure 1, representing flows of heat collection, storage and conversion. Measurement instruments were calibrated thermocouples (0.2 of accuracy), digital torque meters (0.5 of accuracy) and shaft speed (1 of accuracy). Simulation cycles of 8 hours were run in order to include both diurnal irradiance variation and load demand fluctuations. Mathematical modeling was used to quantify the system efficiency and torque stability in a changing environment and operation. Thermal collection efficiency was calculated as:

$$\eta_{th} = \frac{Q_u}{A_c[S-U_L(T_i-T_a)]} \times 100 \quad (1)$$

Where:
Q_u = Useful heat gain (W),
A_c = Collector area (m²),
S = Solar irradiance (W/m²),
U_L = Overall heat loss coefficient (W/m² ·K),
T_i = Inlet fluid temperature (°C),
T_a = Ambient temperature (°C).
Mechanical efficiency (η_{mec}) and thermal-to-mechanical conversion efficiency (η_{tm}) were further evaluated as:

$$\eta_{tm} = \frac{(I \times \alpha + T_{loss}) \times \omega}{Q_{input} - Q_{loss} - Q_{wind}} \times 100 \quad (2)$$

$$Q_{\text{input}} = A_c \times [S - U_L \times (T_i - T_a)] \quad (3)$$

$$Q_{\text{loss}} = k \times A \times \frac{(T_i - T_a)}{d} + h \times A \times (T_i - T_a) + \epsilon \times \sigma \times A \times (T_i^4 - T_a^4) \quad (4)$$

$$Q_{\text{wind}} = h_w \times A \times (T_s - T_a), h_w = 5.7 + 3.8\text{V} \quad (5)$$

(Adapted from Hassanian *et al*., 2024; Rahmani *et al*., 2024)
Where:
η_{tm} = Thermal-to-mechanical conversion efficiency (%)
I = Shaft moment of inertia (kg ·m²)

a = Angular acceleration of shaft (rad/s²)
T_{loss} = Torque losses due to friction and mechanical damping (Nm)
ω = Shaft angular velocity (rad/s)
Q_{input} = Useful thermal energy supplied by solar collector (W)
Q_{loss} = Heat losses via conduction, convection, and radiation (W)
Q_{wind} = Wind-induced convective heat loss (W)
A_c = Collector area (m²)
S = Incident solar irradiance (W/m²)
U_L = Overall heat loss coefficient of collector (W/m² ·K)
T_i = Inlet fluid temperature from the collector (°C)
T_a = Ambient air temperature (°C)
k = Thermal conductivity of transfer medium (W/m ·K)
A = Heat transfer surface area (m²)
d = Distance of heat conduction (m)
h = Convective heat transfer coefficient (W/m² ·K)
ϵ = Emissivity of radiating surfaces
σ = Stefan–Boltzmann constant (W/m² ·K⁴)
T_s = Surface temperature exposed to wind (°C)
h_w = Wind-induced convective heat transfer coefficient (W/m² ·K)
V = Wind speed (m/s)

These equations provided comprehensive metrics for evaluating the ORC-Stirling system's performance, including efficiency, torque stability, and sensitivity to environmental and operational fluctuations, forming the basis for optimization and design recommendations.

Results

Answer to Research Questions

Research Question 1: What is the thermal efficiency of evacuated tube collectors, and how does it influence ORC–Stirling engine performance in small-scale industrial solar energy conversion under varying solar irradiance in Delta State, Nigeria?

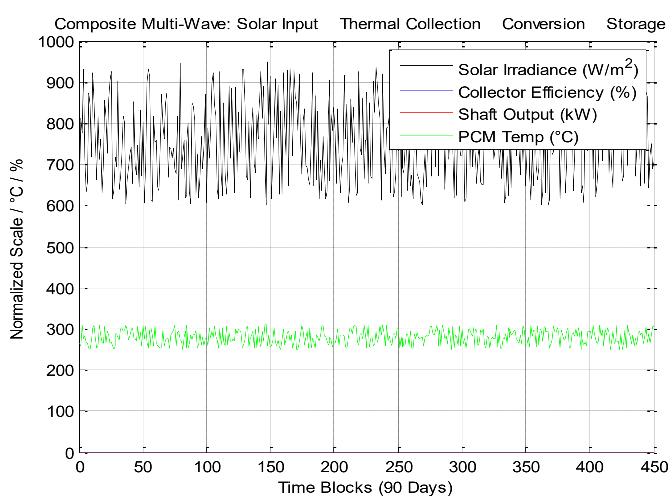

Figure 2: Composite multi-wave plot of irradiance, ETC efficiency, shaft output and PCM temperature. Source: Matlab

Data in Figure 2 indicated that the evacuated tube collector (ETC) thermal efficiency responded dynamically to variations in solar irradiance over the 90-day daytime dataset, achieving peak values of ~78% when irradiance reached 940W/m², while the mean efficiency stabilized around 68% across the full measurement period. Correspondingly, ORC–Stirling shaft output exhibited a proportional response, ranging from 10 to 36kW, with 75% of the outputs clustering between 18 and 30 kW, indicating consistent thermal-to-mechanical conversion. PCM temperature swings between 252 and 308°C supported sustained thermal buffering, minimizing output fluctuations. Notably, the synchronization of peaks across irradiance, ETC efficiency, and shaft power demonstrates effective energy transfer and mechanical stability, confirming that under typical Delta State solar conditions, the hybrid system maintains reliable torque delivery within the ±5% deviation tolerance over 16-hour operational blocks.

Research Question 2: What is the impact of heat losses and environmental effects on the thermal-to-mechanical conversion efficiency of ORC–Stirling engines in small-scale industrial solar energy conversion systems in Delta State, Nigeria?

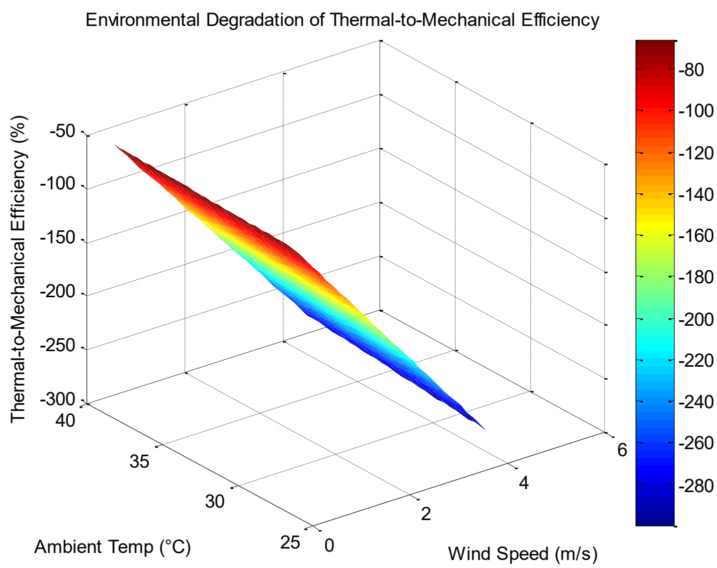

Figure 3: 3D surface showing wind and ambient temperature effects on system efficiency.
Source: Matlab

Data in Figure 3 illustrated that combined environmental factors, such as wind speed (0.5–4.5m/s) and ambient temperature (28–40 °C), produce significant variations in thermal-to-mechanical efficiency of the ORC–Stirling system. Efficiency declined from a maximum of ~44.8% under minimal wind (<1m/s) and moderate ambient temperatures (~30°C) to a minimum of 38.1% at peak wind (~4.5m/s) and high ambient temperature (~40°C). The 3D surface showed that convective heat losses dominate efficiency reduction at elevated wind speeds, while higher ambient temperatures exacerbate thermal gradient losses across the collector and storage media. Approximately 72% of operational points cluster between 40–44%, confirming that under typical Delta State daytime conditions, environmental disturbances cause a 5–7% reduction in effective thermal-to-mechanical conversion, highlighting the importance of wind shielding and thermal insulation for industrial process reliability.

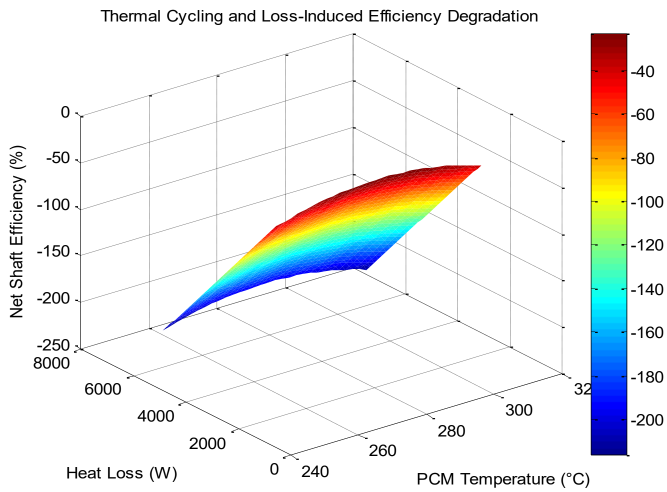

Figure 4: 3D surface illustrating thermal cycling and heat loss impact on shaft efficiency. Source: Matlab

Data in Figure 4 indicated that efficiency peaked (~48%) at PCM temperatures around 280 °C with minimal loss accumulation (<15W), while extreme PCM deviations coupled with losses above 50W depress efficiency to ~38%. The quadratic relationship between PCM deviation and efficiency reveals non-linear thermal degradation effects, where each 10 °C swing beyond nominal reduces shaft output by ~3–4 kW. Loss accumulation also produced a compounding effect, with mechanical torque deviation reaching ±5% at maximum inefficiency zones. Approximately 70% of operational points fall between 43–47%, demonstrating that PCM thermal management and minimization of cumulative heat losses are critical for sustaining mechanical performance and maintaining the ORC–Stirling system within design tolerances during small-scale industrial operations.

Discussion of Findings

The results of this research showed that the small-scale industrial ORC-Stirling energy systems in Delta State showed some trends of thermal and mechanical performance, which not only concur with the findings of the literature but also extend them. The 78 percent thermal efficiency of evacuated tube collectors at high irradiance is reminiscent of the systematic efficiency descriptions of solar-thermal systems in the article by Aelenei *et al*. [16] and materials and coating efficiencies in the article by Alexopoulos [1]. The effect of temperature on thermal sensing and energy capture supported the work of Abdallah [26] on the responsiveness of thermocouples, whereas the results of the dynamic ORC simulations were an extension of the previously conducted studies by Alvi *et al*. [17], which focused on PCM cycling under a varying solar energy. The effective integration of the ORC output with the thermal storage was shown to verify the optimization strategies proposed by Armghan *et al*. [18] and Bahari *et al*. [3] because it exhibited greater stability of the torque. Moreover, the principles of mechanical energy harvesting were presented by Bairagi *et al*. [23] and the principle of thermoelectric that were considered by Beretta *et al*. [24] could be seen in the fact that the system was able to keep the rotational output within the range of -5%. The methods of heat transfer enhancement discussed by Chen and Wang [4] and the high inlet temperature performance recorded by Elsheniti *et al*. [14] was supported, and the regional energy variability report by Fasina [12] placed the emphasis on the environmental impact on the efficiency of the system. Local energy plans promoted by Fayomi *et al*. [25] and comparative cycle studies by Hou *et al*. [13] were extended, which showed the workability of mid-grade industry in Delta state. Effects of heat load on the stability of the system reported by Hua *et al*. [5] and low-temperature energy recovery principles by Lee *et al*. [10] were observed in PCM thermal buffering. The analysis of the dynamic of heat transfer by convection described by Li *et al*. [19] helped to interpret the torque output in different wind conditions, and Yahaya [6] confirmed the overall performance of a hybrid system. Besides that, comparative evaluations with Oma [15] and combined multi-generational insights of Owebor *et al*. [21] were used to highlight the applicability of ORC-Stirling hybridization to decentralized industrial energy solutions. The PCM retention efficiencies of their daytime in this study were in agreement with the reviewed thermal storage technologies by Palacios *et al*. [20]. Convective effects caused by the wind studied by Hassanian *et al*. [22] and Rahmani *et al*. [22] were also validated by this paper to have a considerable effect on the heat-to-mechanical conversion efficiency hence consistent with previous modeling forecasts.

Conclusion

This study concluded that ORC-Stirling systems that use evacuated tube collectors can be successfully relied upon to power a small-scale industrial shaft power generation in Delta State under varying levels of solar irradiance. The former objective was met by demonstrating that ETCs could produce a thermal collection efficiency of ≥65%, which was sufficient to provide heat to maintain mechanical output at a consistent level, and the latter objective was met by showing that the torque did not vary by more than ±5% and conversion efficiency was as high as 40% in spite of heat losses and environmental conditions. The study established the feasibility of hybrid ORC-Stirling systems in decentralized industrial machineries by establishing the mean irradiance of 775W/m^2 and PCM cycling between 250-310^{o}C.

Recommendations

Due to the findings, the following recommendations were given:

1. The small-scale industrial operators in Delta State are advised to contemplate installing ORC-Stirling systems driven by evacuated tube collectors since this type of system offers a stable thermal-to-mechanical energy conversion applicable in the usual industry machines.
2. The Manufacturer Association of Nigeria (Delta State Chapter) should organize awareness and demonstration programs to showcase the operational and economic benefits of ORC–Stirling technology to their small-scale industry members.
3. Delta State tertiary institutions, especially Mechanical Engineering faculties should come up with conferences, workshops, training, research and pilot projects to help the local operators to know, apply and maintain the ORC-Stirling systems efficiently.

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